

Intense Beams of Energetic Heavy Ions as a Tool Study High Energy Density States in Matter

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Definition:

States that correspond to an energy content of 10^{11} J/m³ or equivalently **1 Mbar** pressure [**HED states**].

Importance:

Spans over wide areas of basic and applied physics
For example; astrophysics, planetary sciences, geophysics, inertial fusion, strongly coupled plasmas and many others.

In addition to that, HED matter has great potential for numerous lucrative industrial applications.

Due to these reasons, research on thermophysical properties [Equation-of-State] of HED matter has been a hot topic over past many decades.

Traditional Methods

1. **Shock compression of matter**

- a) high power chemical explosives
- b) gas guns
- c) high power lasers
- d) nuclear explosions

2. **Exploding wire**

3. **Static compression in a diamond anvil cell**

New Approach

Substantial advancement in the technology of strongly bunched, well focused, high intensity ion beams [**new concept**].

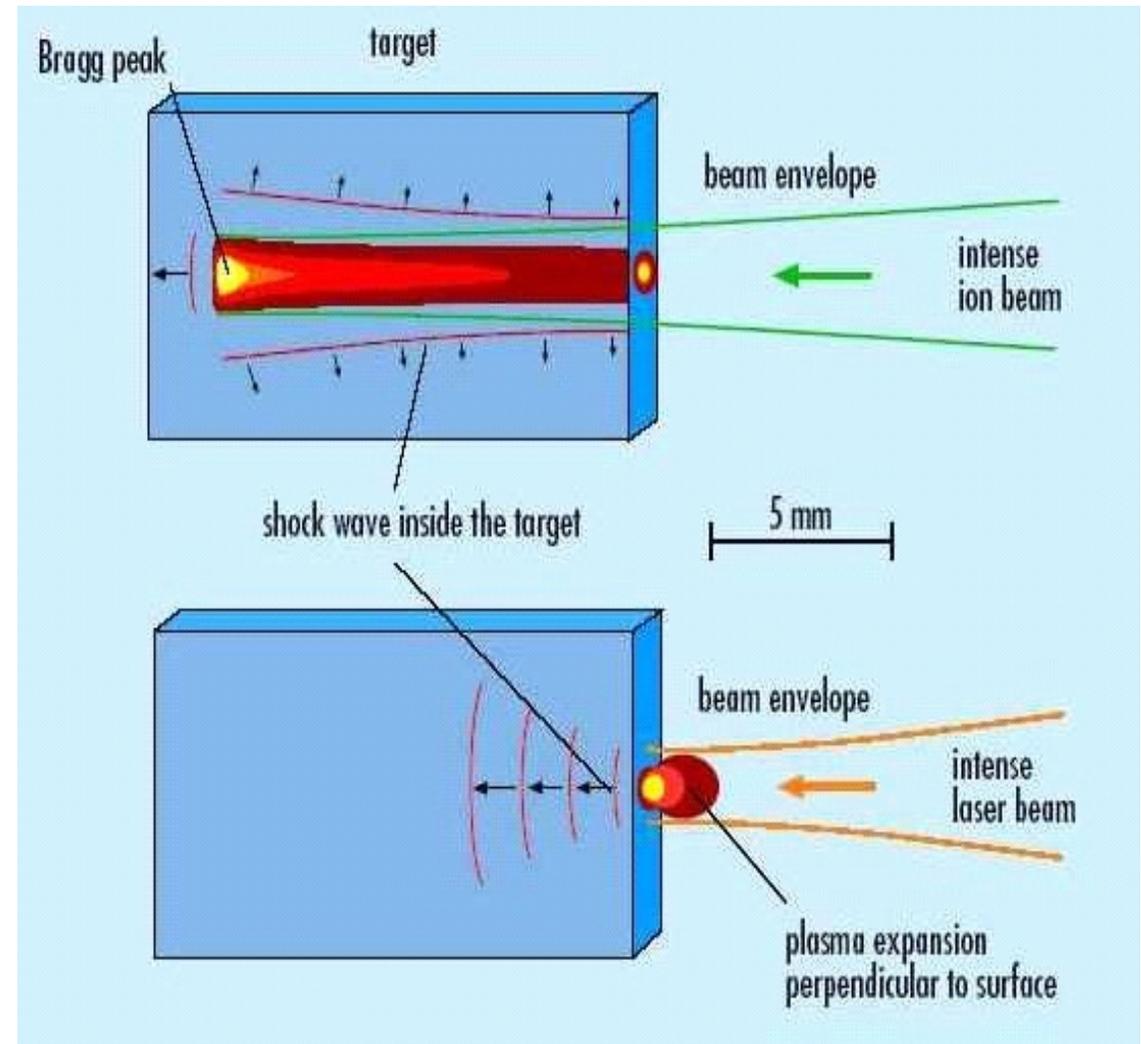
Creation of HED matter using **isochoric** and **uniform** target heating by intense ion beams. [**shockless**]

Beam Generation:
traditional accelerators
petawatt lasers

accelerator generated beam have numerous advantages over **laser** generated ones

Advantages of Using Ion Beams to Heat Matter

1. Large samples [$\text{mm}^3 - \text{cm}^3$].
2. No sharp gradients [uniform physical conditions].
3. Long life times [10 – 100 ns].
4. Precise knowledge of energy deposition.
5. Wide range of particle energy [flexibility for designers].



Specific power deposition:

$$P = \frac{E_s}{\tau}, \quad \text{TW/g}$$

$$E_s = \frac{\frac{1}{\rho} \frac{dE}{dx} N}{\pi r_b^2}, \quad \text{kJ/g}$$

$\frac{1}{\rho} \frac{dE}{dx}$: specific energy loss due to a single ion

N : total number of particles in the beam

r_b : beam radius

Important Parameter:

**Determines Level of
Target Heating**

The new synchrotron, SIS-100 that will be built at the future **FAIR** [Facility for Antiprotons and Ion Research] facility, will deliver a uranium beam with two orders of magnitude higher intensity than what is currently available at the existing SIS-18 synchrotron.

SUMMARY OF PARAMETERS

	SIS-18	SIS100	
Intensity	4x10⁹	10¹²	[x 250]
Bunch Length	130 ns	50 ns	
Beam Energy	0.06 kJ	76 kJ	
Particle Energy	400 MeV/u	0.4 – 2.7 GeV/u	
FWHM	1.0 mm	1.0 mm	
Specific Energy Deposition in Pb	1 kJ/g	250 kJ/g	[x 250]
Specific Power Deposition in Pb	5 GW/g	6 TW/g	[x 1200]

Beam-Target Heating Using U Beam

N.A.Tahir et al., PRE 61 (2000)1975

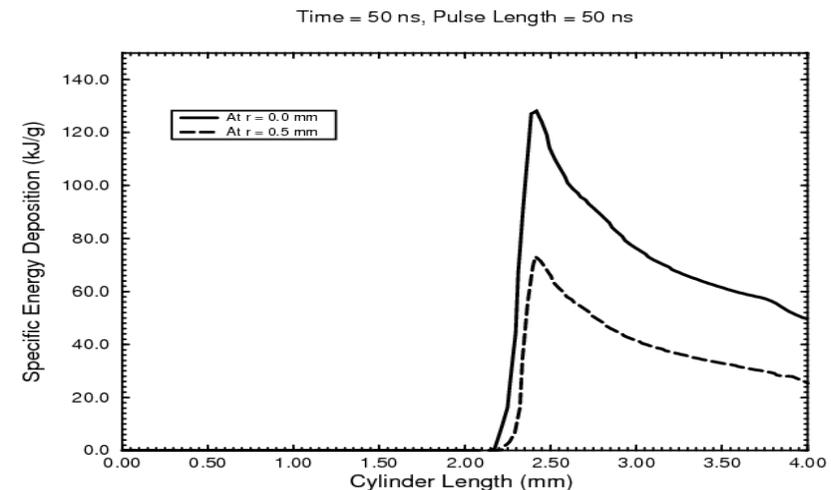
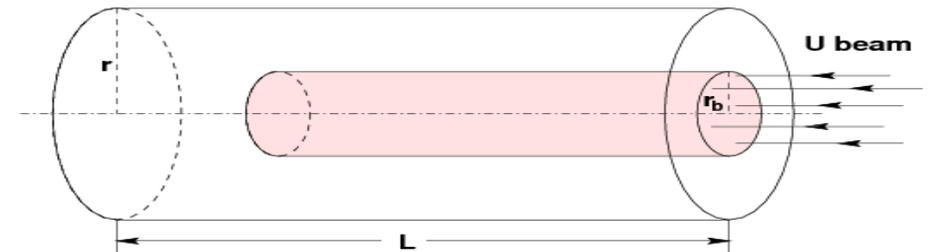
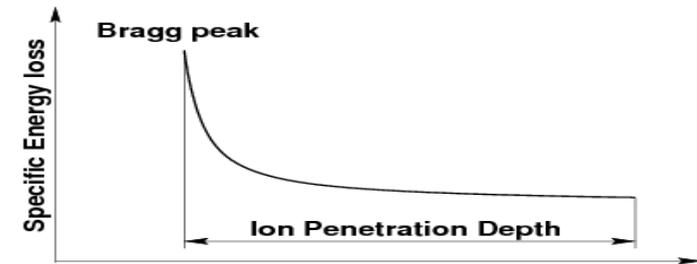
**2D Hydrodynamic Simulations
Using Code BIG2: ALE scheme**

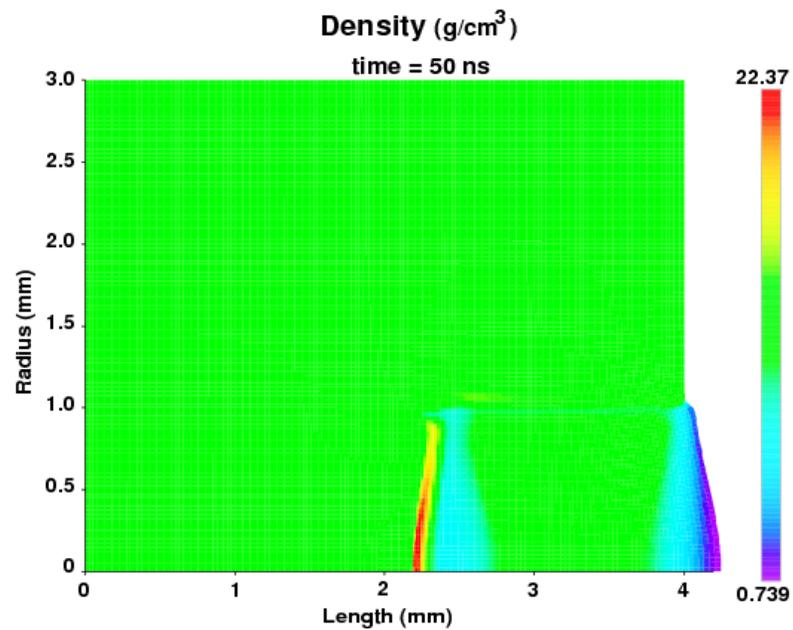
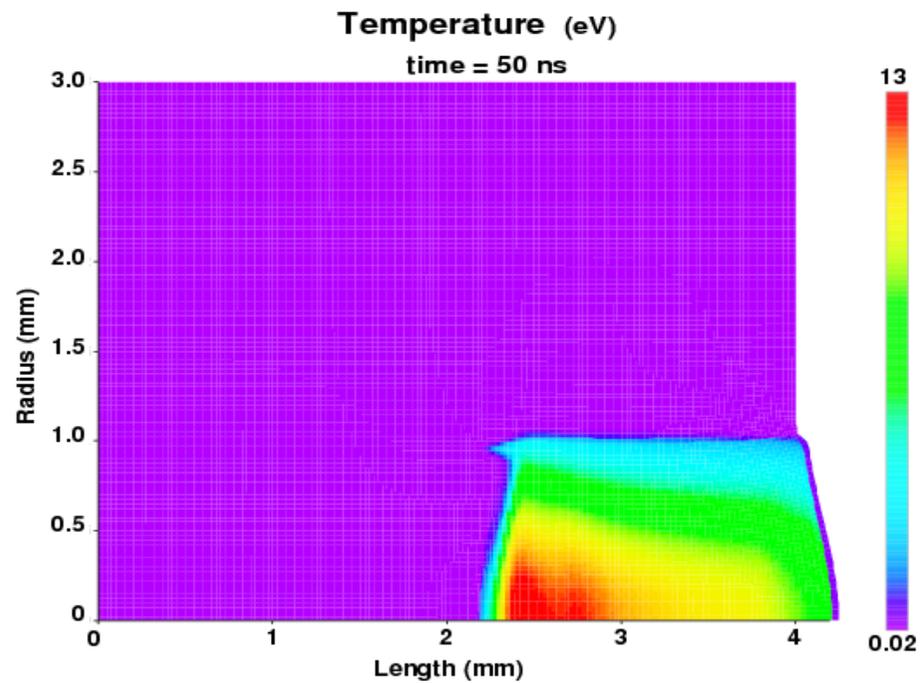
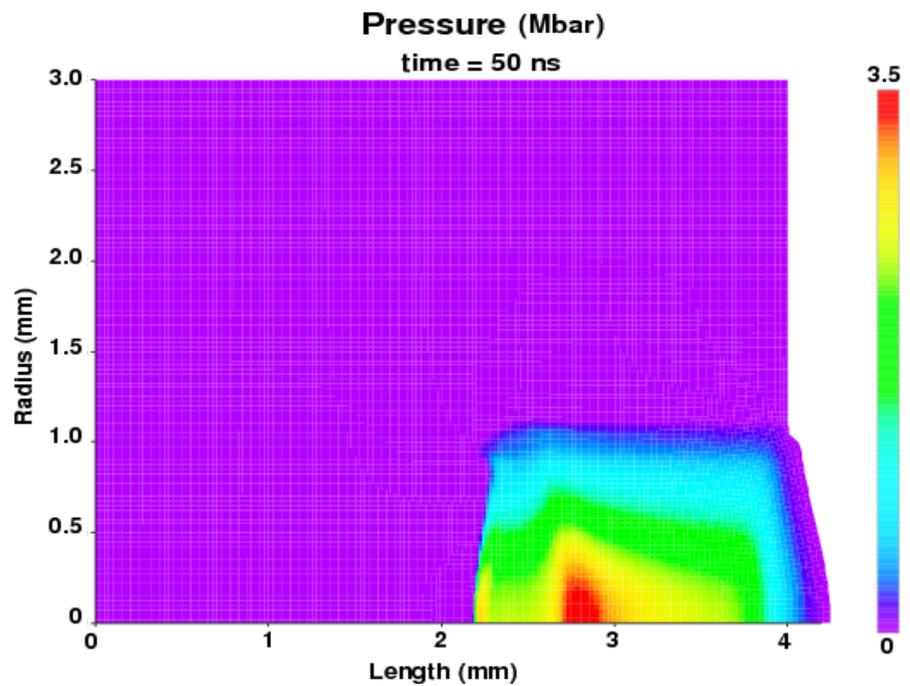
**solid lead cylinder, $L = 4$ mm,
 $r = 3$ mm**

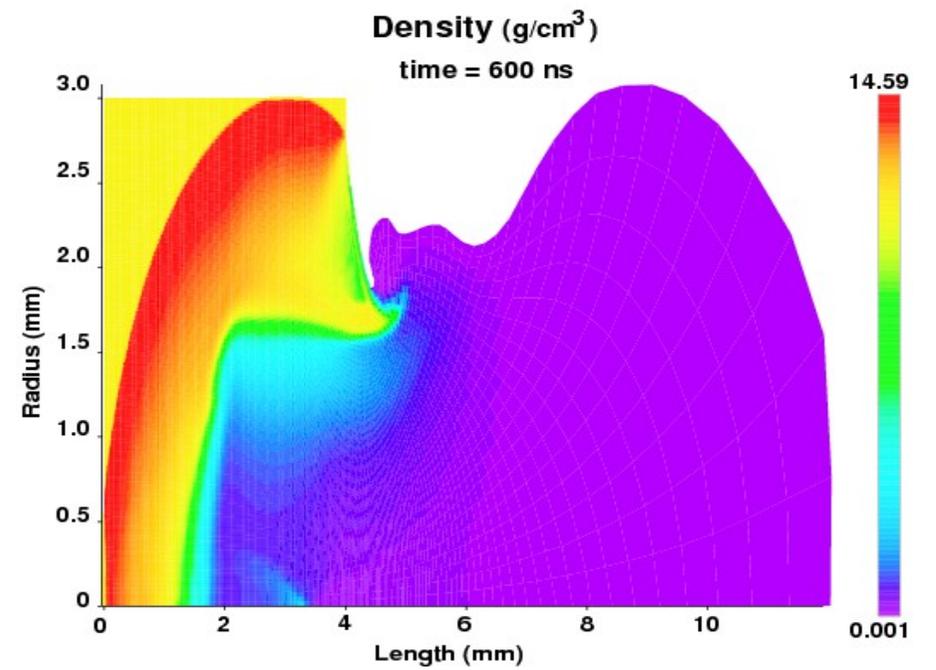
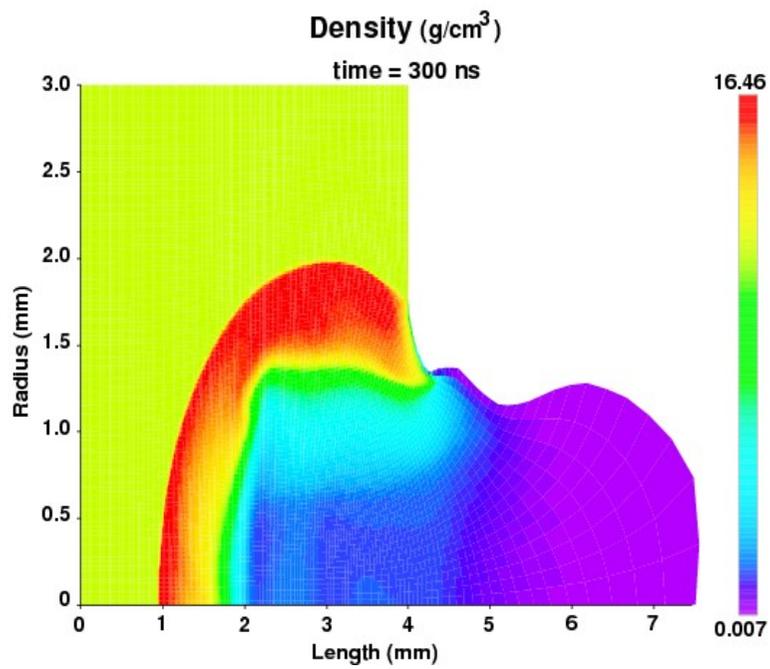
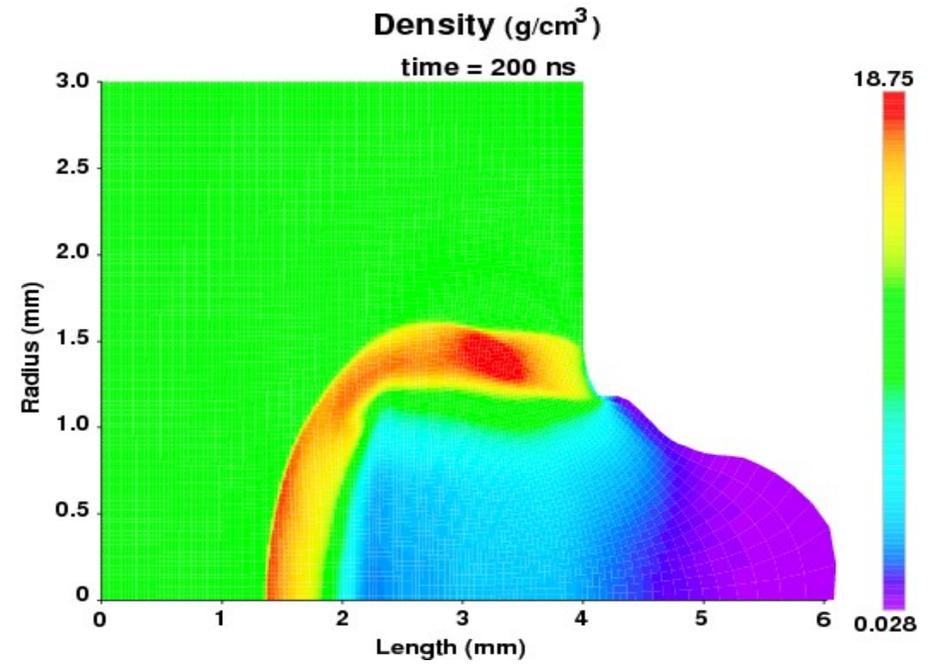
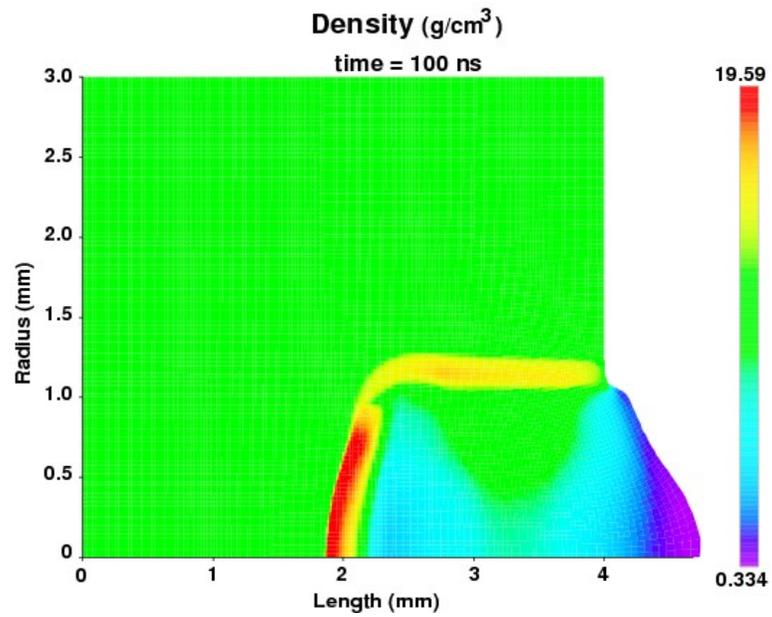
**U beam (200 MeV/u),
 $N = 2 \times 10^{11}$ ions $\tau = 50$ ns,**

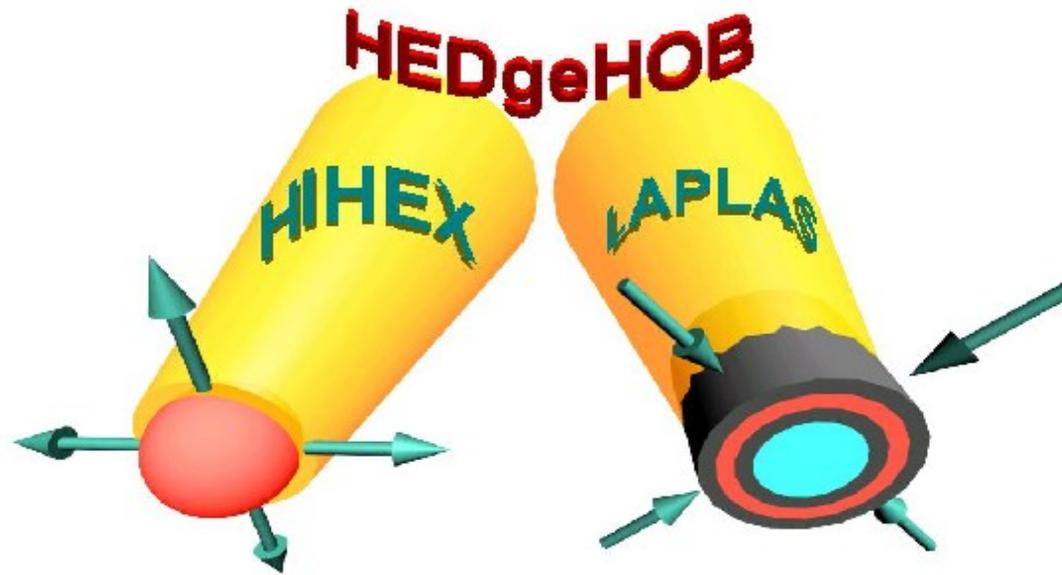
**Gaussian distribution in
transverse direction
FWHM = 1 mm**

Ion Range = 1.68 mm









HEDgeHOB [High Energy Density Matter Generated by Heavy Ion Beams]

HIHEX [Heavy Ion Heating and Expansion]

LAPLAS [Laboratory Planetary Science]

Ramp Compression

HIHEX [Heavy Ion Heating and Expansion

This technique involves isochoric and uniform heating of matter by an intense ion beam and the heated material is allowed to expand isentropically.

Expanded Hot Liquid

Two-Phase Liquid-Gas Region

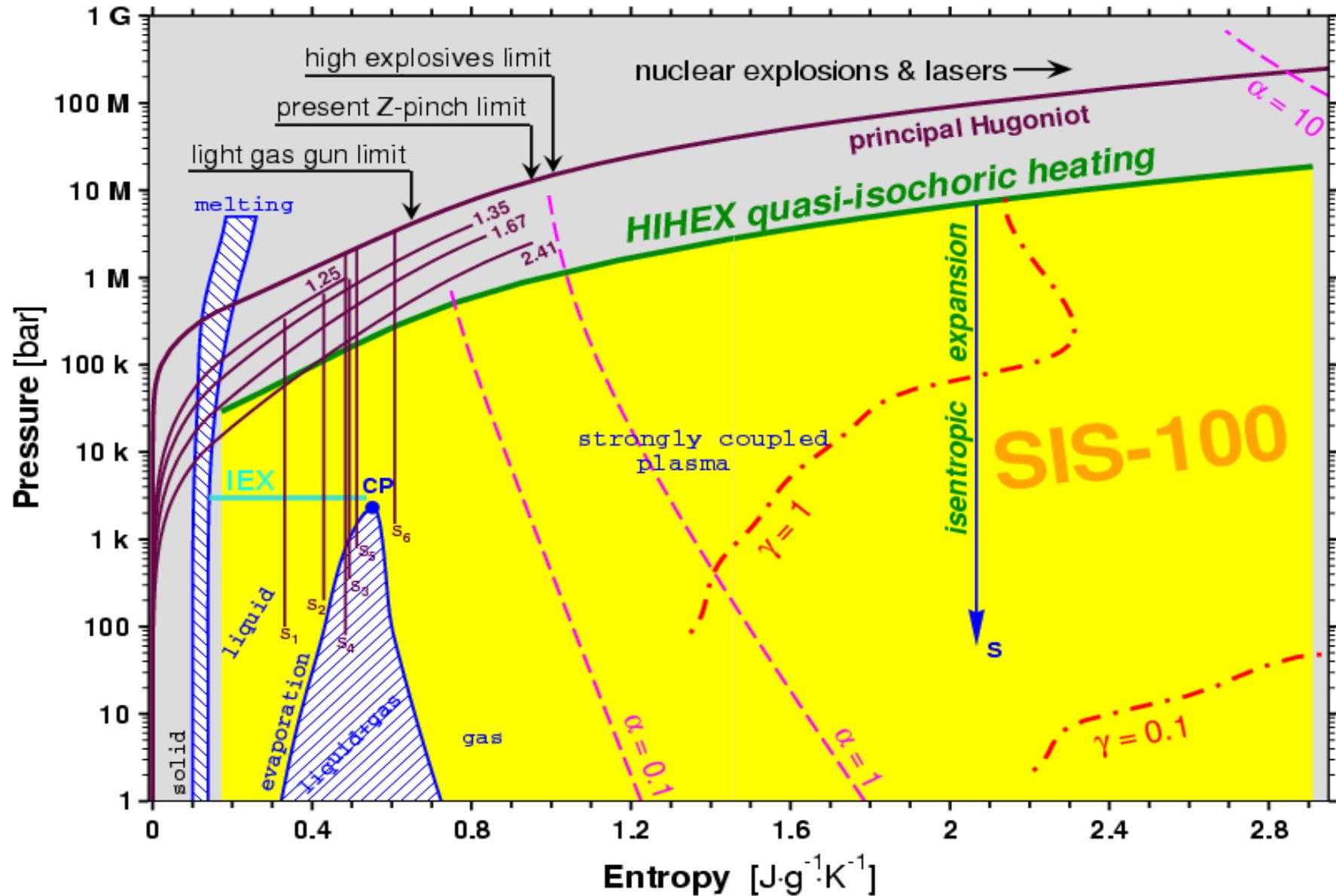
Critical Parameters

Strongly Coupled Plasma

References:

- 1) D.H.H. Hoffmann et al., Phys. Plasmas 9 (2002) 3651.**
- 2) N.A. Tahir et al., Phys. Rev. Lett. 95 (2005) 035001.**

Phase diagram of lead

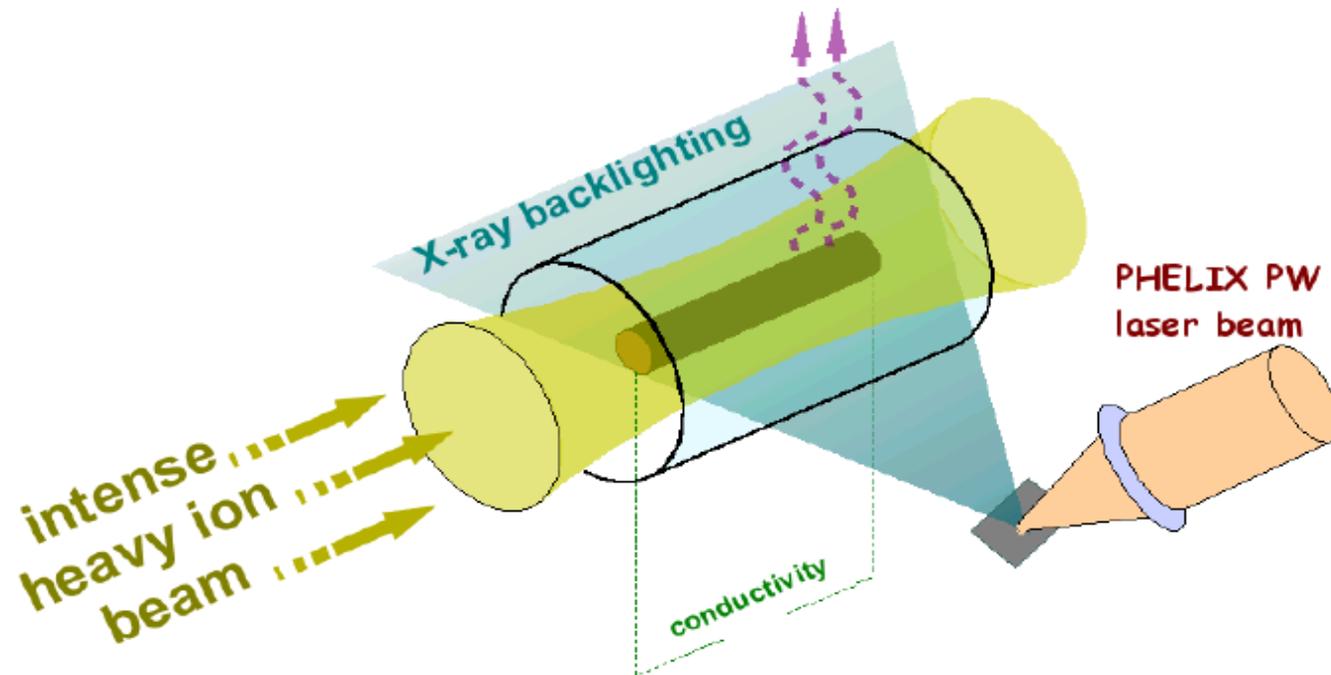


Critical Parameters of Some Metals

I.V. Lomonosov and V.E. Fortov

	T_c (K)	P_c (kbar)	ρ_c (g/cm ³)
Aluminum	6390	4.45	0.86
Copper	7800	9.00	2.28
Gold	8500	6.14	6.10
Lead	5500	2.30	3.10
Niobium	19200	11.1	1.70
Tantalum	14550	7.95	3.85
Tungsten	13500	3.10	2.17
Beryllium	8600	2.00	0.40

Cylindrical HIHEX Experiment Design Using Solid Material



Numerical Simulation Results:

Target Parameters:

Solid lead cylinder, $L = 2 - 3$ mm, $r = 300 - 500$ μm

Beam Parameters:

Uranium Beam

Particle Energy = 1 GeV/u

Beam Intensity = $10^{10} - 10^{11}$ ions / bunch

Bunch Length = 50 ns

Early and Intermediate Stages of FAIR

Simulation Results from a Typical Case

- Solid Lead Cylinder
- $L = 2 \text{ mm}$, $r = 300 \text{ }\mu\text{m}$
- $N = 2.5 \times 10^{10}$
- Bunch Length = 50 ns
- Beam spot Size (FWHM) = 2 mm

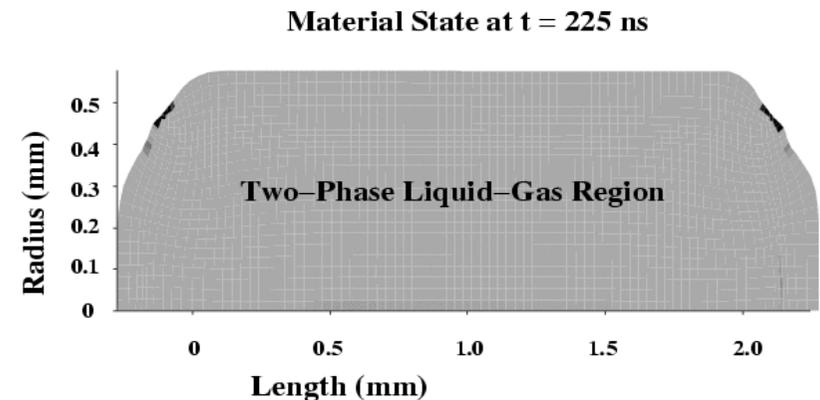
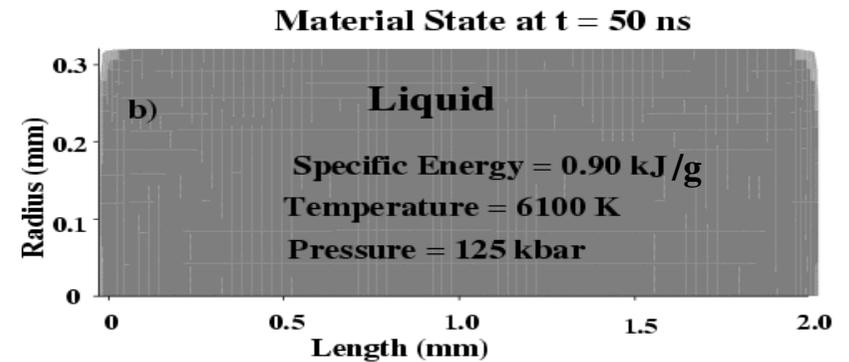
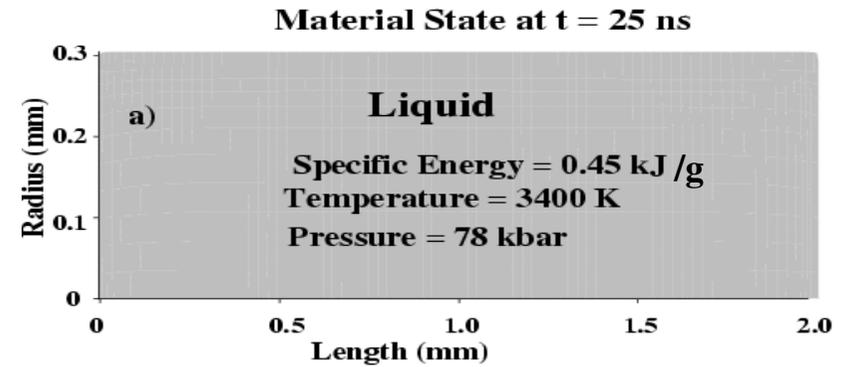


Table 1: Final Achievable Material State

Intensity	FWHM (mm)	Material State
10^{11}	1	SCP
	2	SCP
	3	CP
	4	2PLG
$7.5 \cdot 10^{10}$	1	SCP
	2	G
	3	2PLG
	4	2PLG
$5 \cdot 10^{10}$	1	SCP
	2	EHL
	3	2PLG
$2.5 \cdot 10^{10}$	1	G
	2	2PLG
	3	2PLG
10^{10}	1	2PLG
	2	2PLG

SCP : strongly coupled
plasmas

CP : critical point

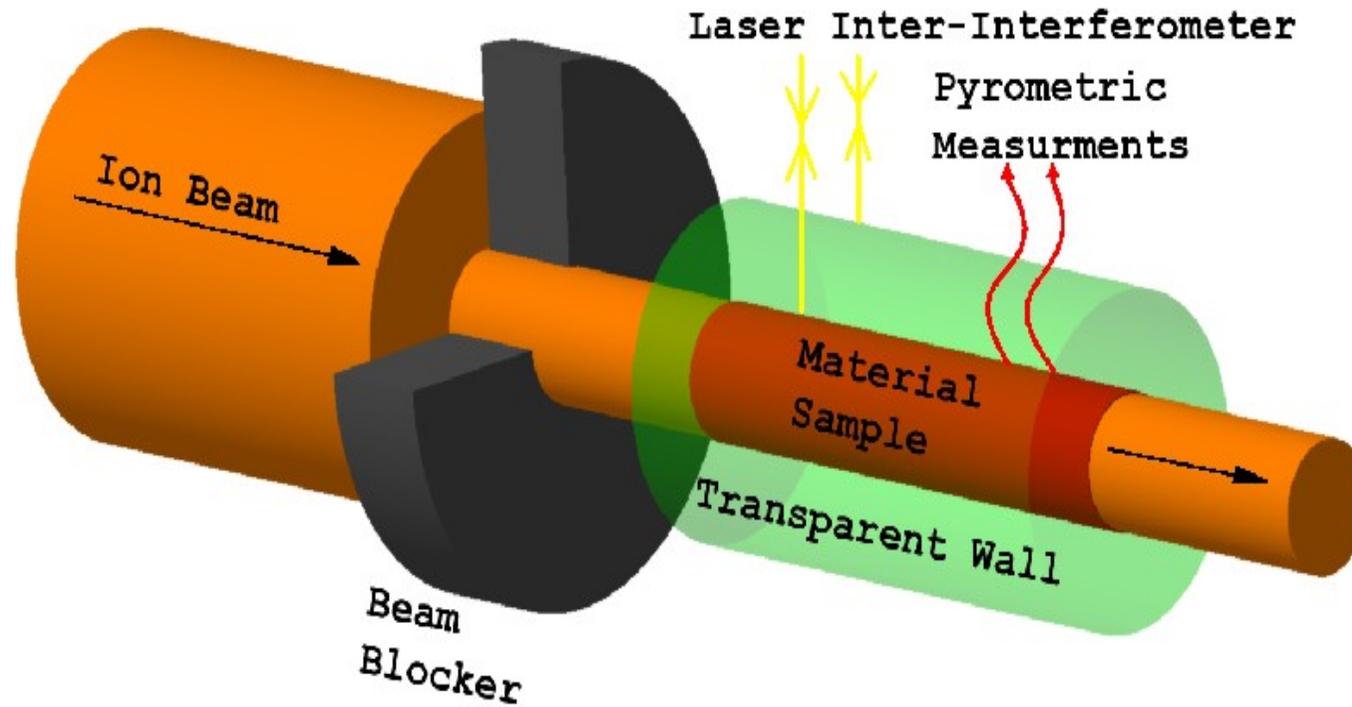
2PLG: two-phase
liquid-gas

EHL : expanded hot liquid

G : Gas

HIHEX Using Porous Material

N.A. Tahir et al., High Energy Density Phys. 2 (2006) 21.



1 GeV/u uranium beam

$N = 5 \times 10^{11}$, $\tau = 50$ ns

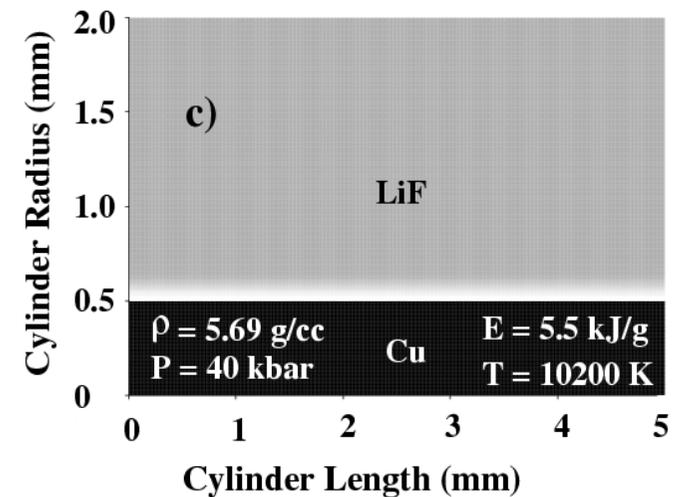
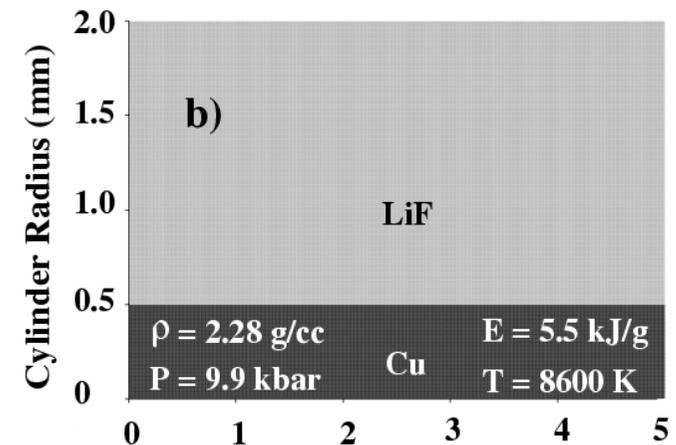
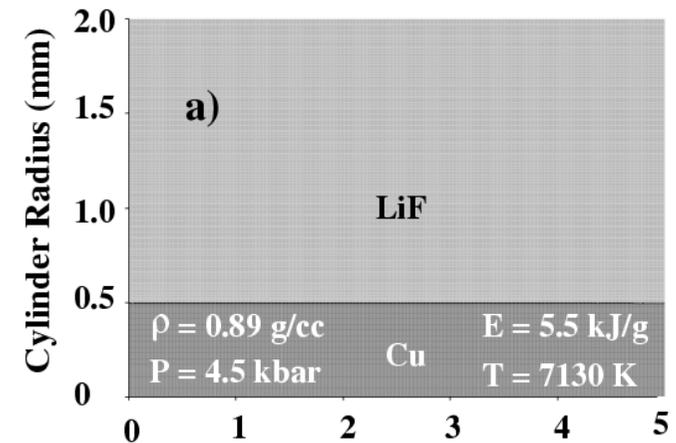
FWHM = 4 mm

$E_s = 5.5$ kJ/g

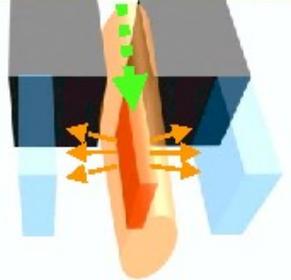
FWHM = 2 - 4 mm

$N = 10^{11} - 10^{12}$

$\Gamma = 5$



Heavy Ion Heating and Expansion



Target Construction

- Tungsten diaphragm
- Sapphire
- Target foil

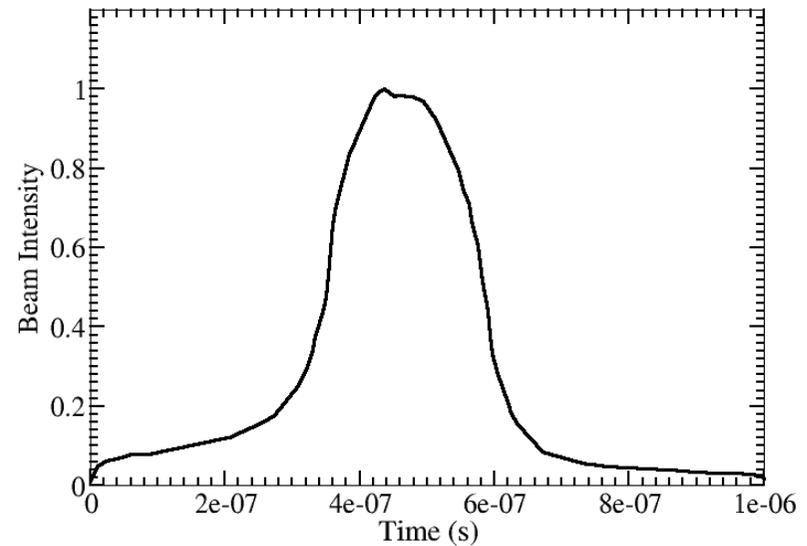
Practical Target

- Brass container

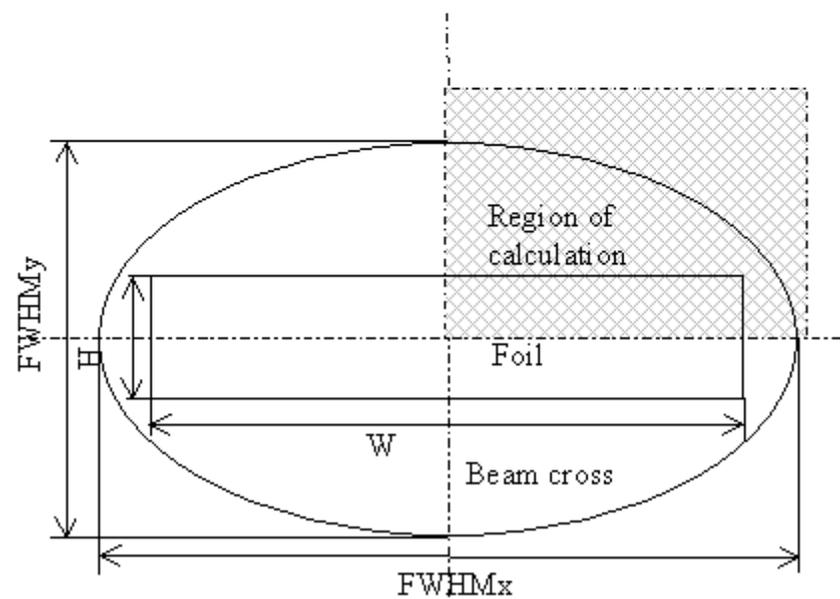
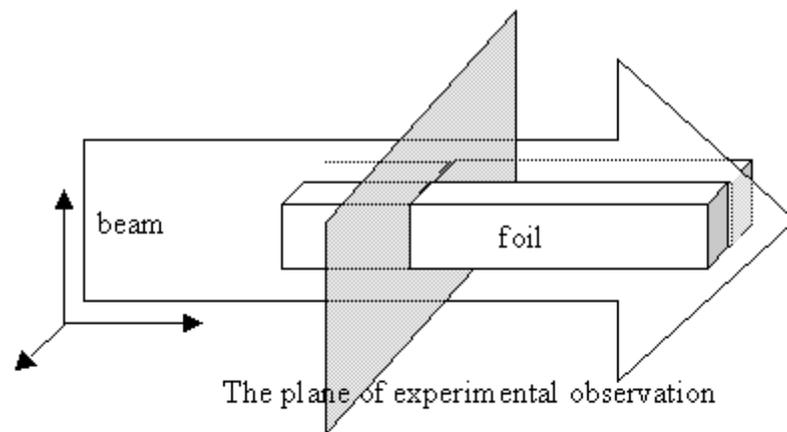
Target manipulator

Beam Intensity Profile [U]

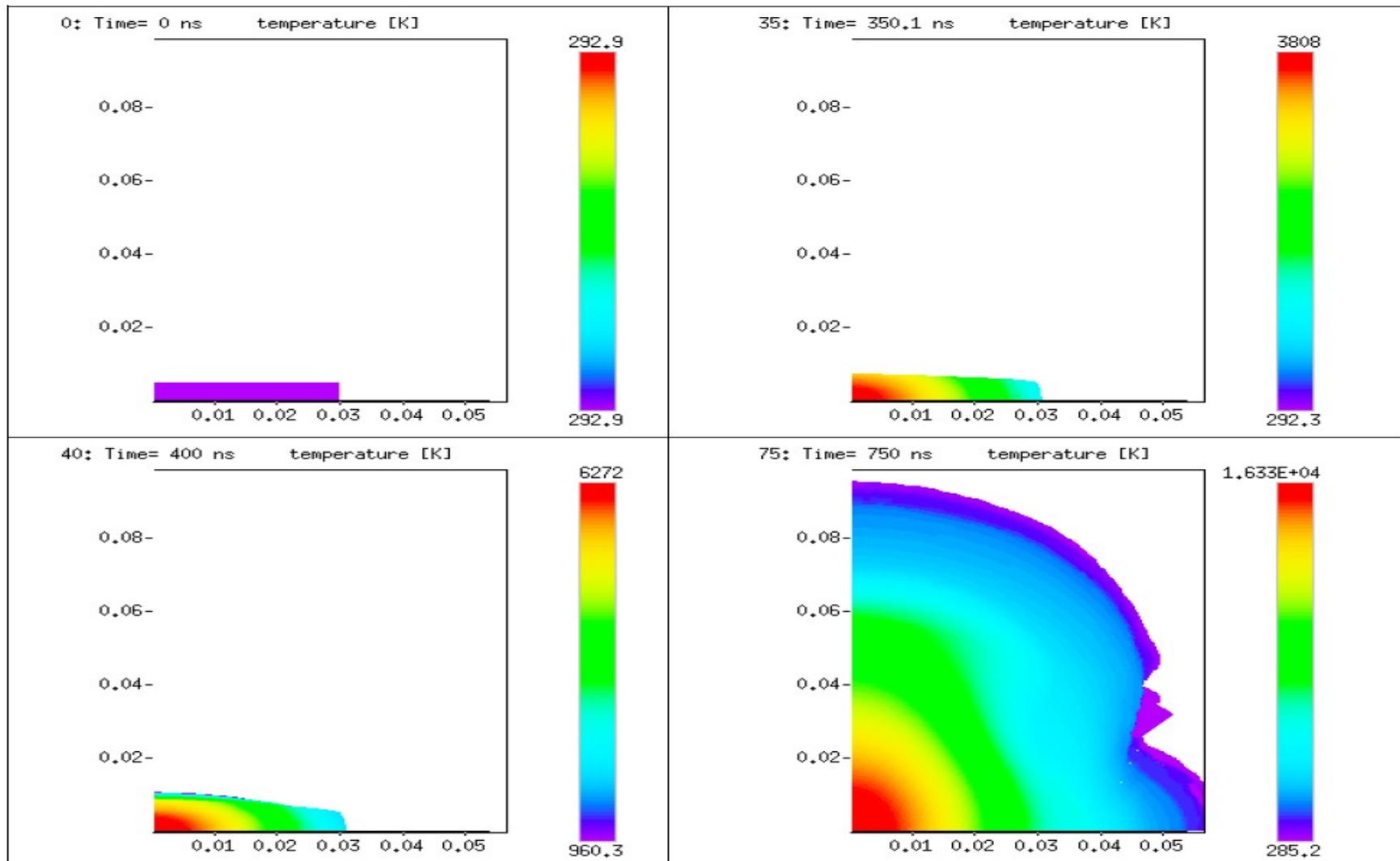
- $N = 2 \times 10^9$ / bunch
- $E = 350$ MeV/u
- $\text{FWHM}_x = 0.45$ mm
- $\text{FWHM}_y = 0.30$ mm



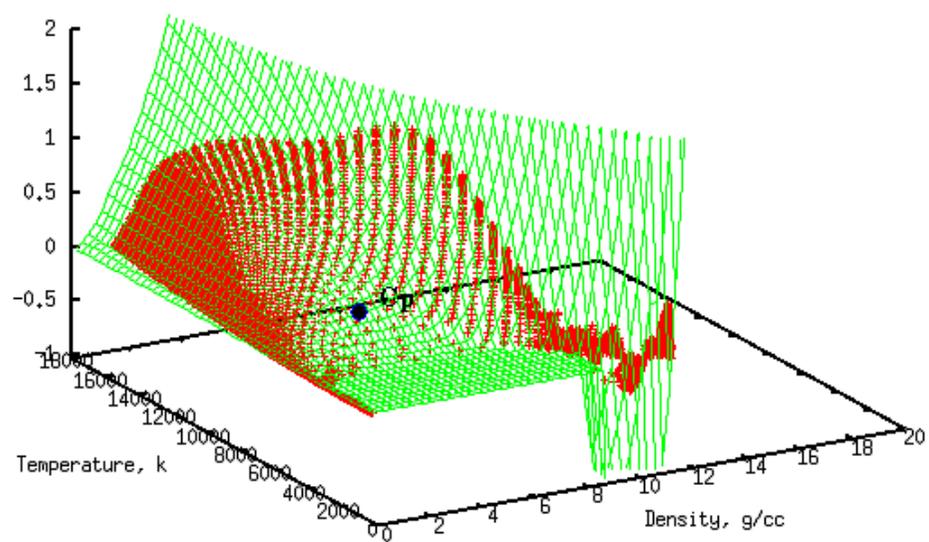
N.A. Tahir et al., Nucl. Inst. Meth. A 577 (2007) 238 - 249



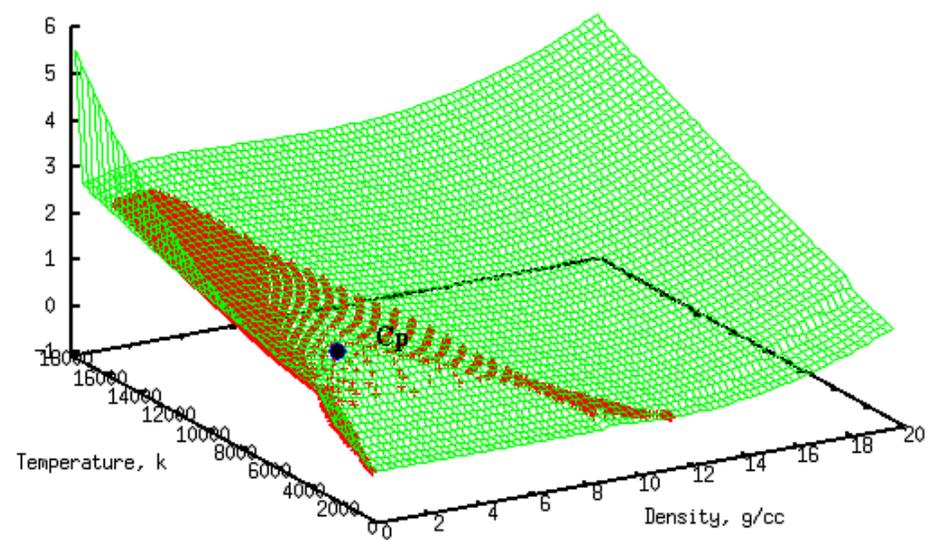
Lead Target



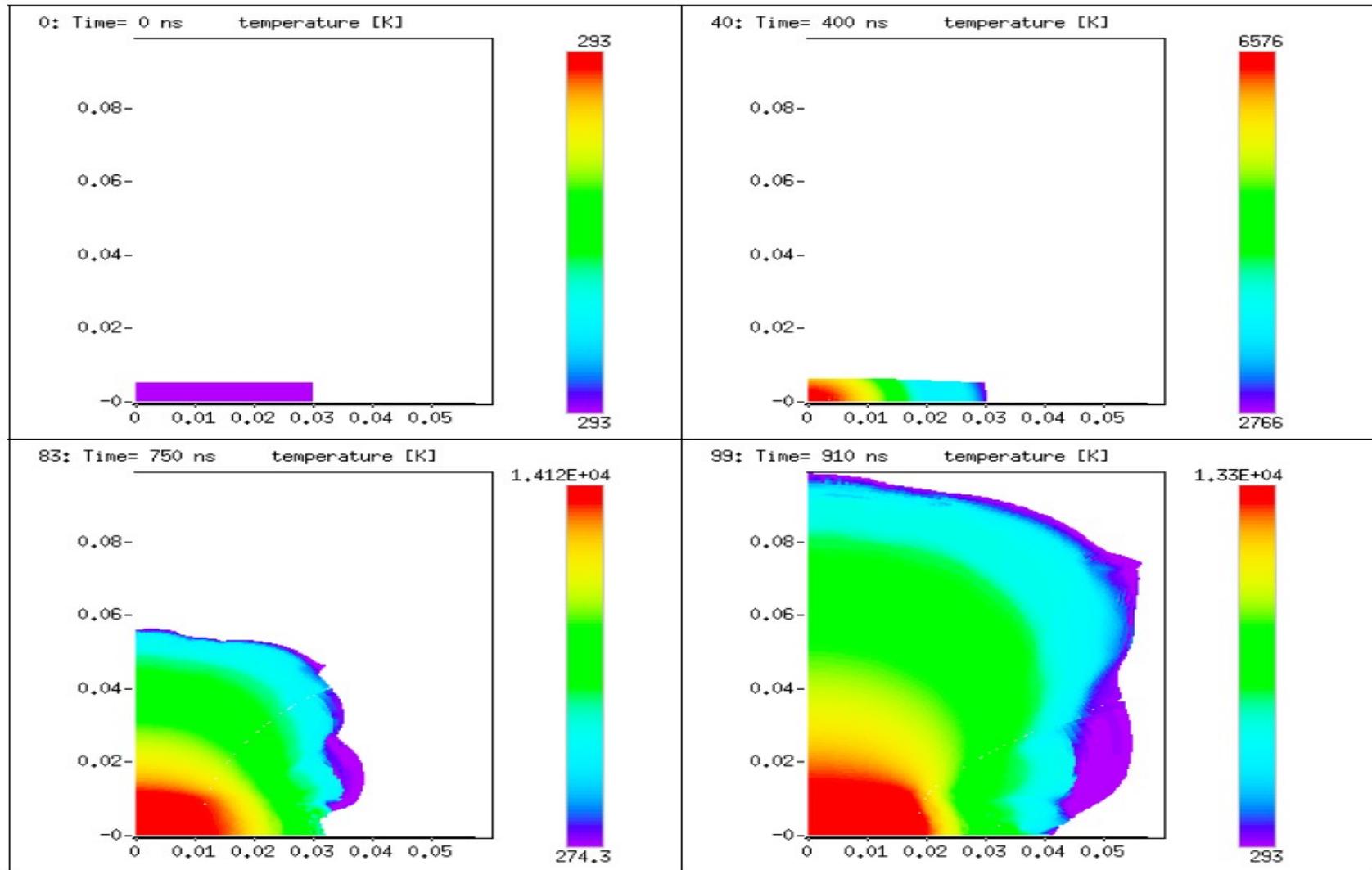
Pressure, Gpa



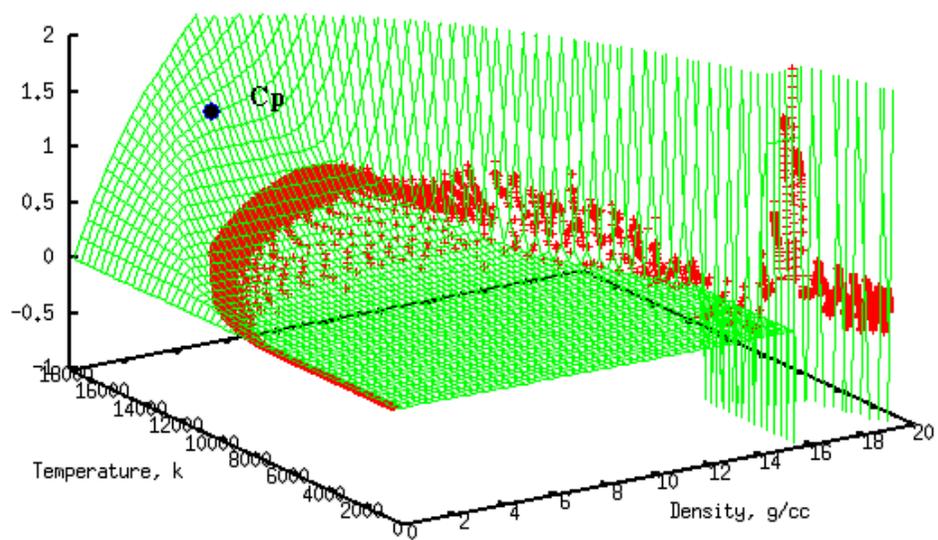
Energy, kJ/g



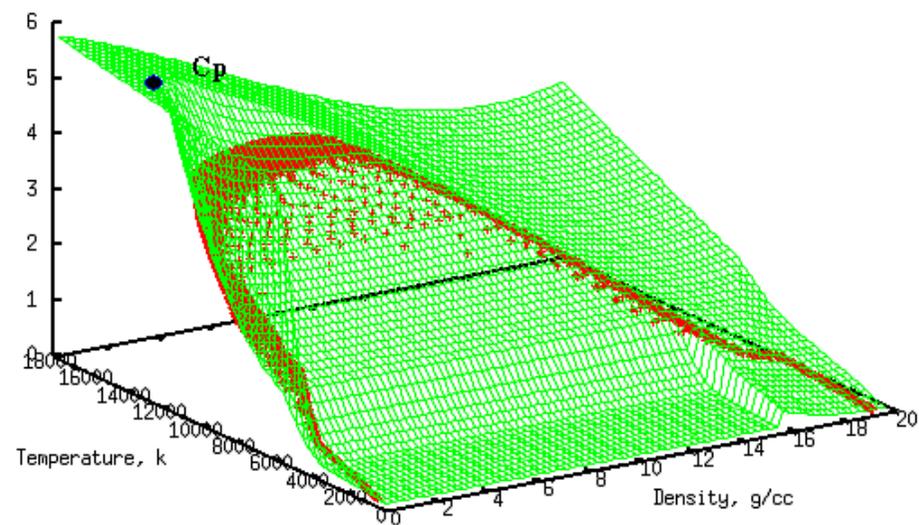
Tungsten Target



Pressure, Gpa



Energy, kJ/g



LAPLAS [LABoratory PLANetary Sciences]

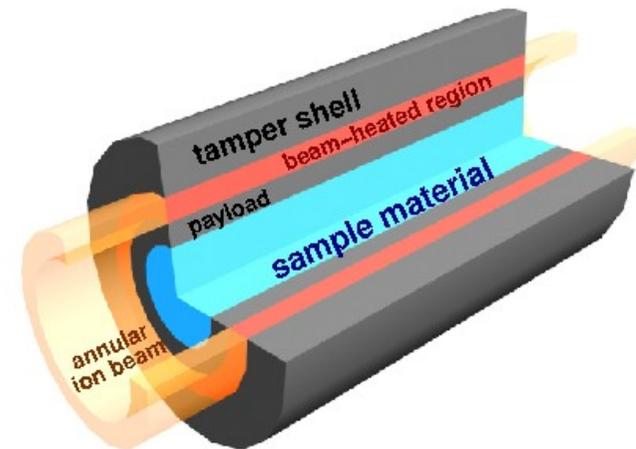
Experimental Scheme:

Low-entropy compression of a test material like hydrogen, in a multi-layered cylindrical target.

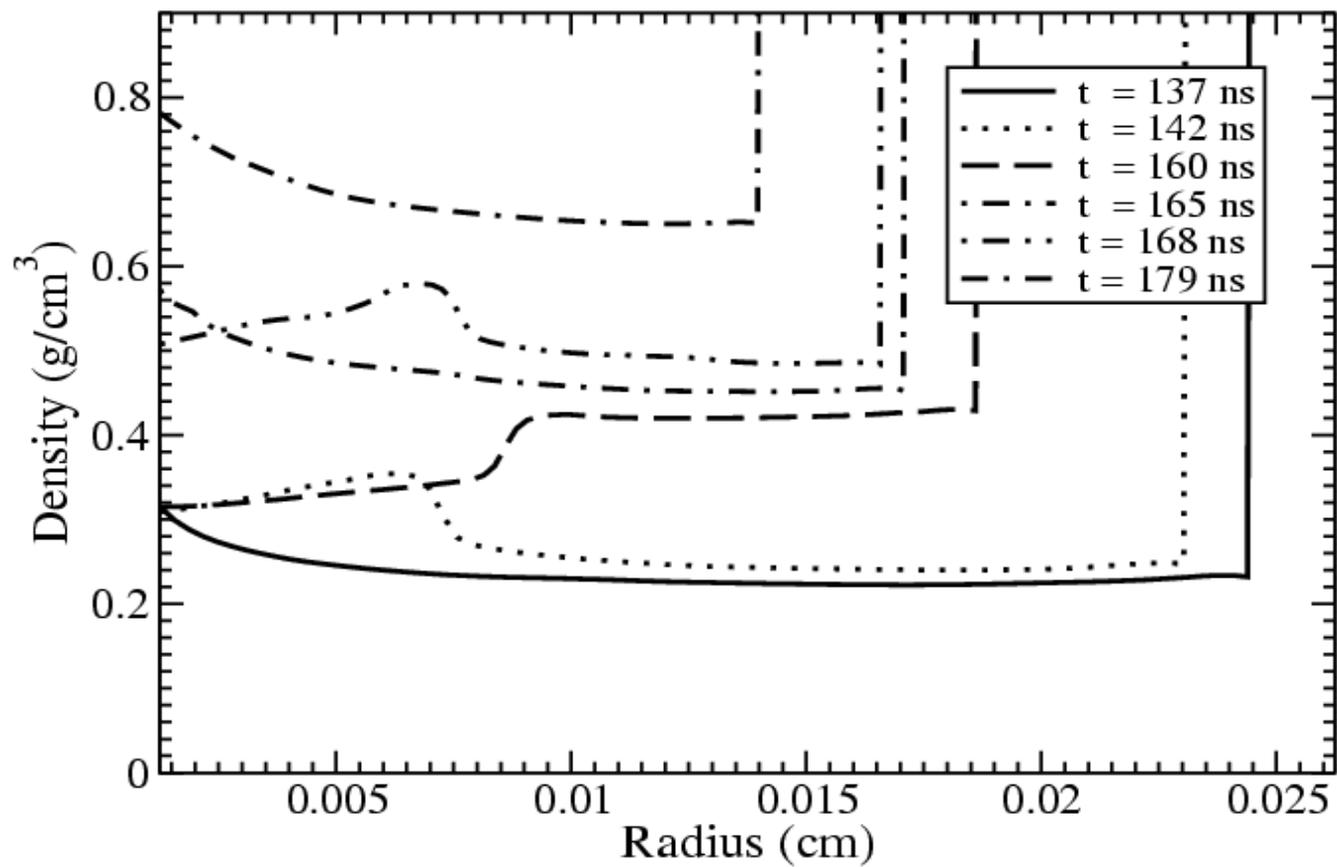
N.A. Tahir et al., *Phys. Rev. E* 64 (2001) 016202

Phys. Rev. B 67 (2003) 184101.

- Shock reverberates between the cylinder axis and the hydrogen-outer shell interface.
- super high densities, ultra high pressures, low temperatures.
- $\rho = 1-2 \text{ g/cm}^3$, $P = 2-15 \text{ Mbar}$ and $T = \text{few kK}$



1 GeV/u U ions, $N = 5 \times 10^{11}$, Bunch length = 50 ns



Hydrogen Under Extreme Conditions

WIGNER & HUNTIGTON, J. Chem. Phys. 3 (1935) 764.

Predicted hydrogen will metallize under pressure of 0.25 Mbar

Later, exotic properties were predicted for metallic hydrogen

ASHCROFT, PRL 21 (1968) 1748.

Room Temperature Superconductor

BROVMAN et al., Sov. Phys. JETP 34 (1972) 1300.

Metastable [sample will remain intact after pressure is released]

It could be a clean and efficient fuel for rocket propulsion

Technological developments in **HIGH PRESSURE** Physics lead to very active research to investigate this problem [Static as well as Dynamic schemes have been used]

B. Analytic Modeling

1. Simulations of the LAPLAS scheme were followed by development of an analytic model to analyze the implosion dynamics of the target. [[A.R. Piriz et al., Phys. Rev. E 66 \(2002\) 056403](#)].

If

the **hydrogen mass** \ll **the payload mass**

and

the payload mass \ll **the absorber mass**

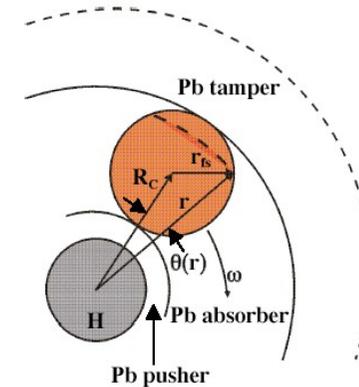
The compression results are very insensitive to large variations in the beam and target parameters. The scheme is therefore very robust which is a very important result for the experimentalists.

2. Generation of an annular focal spot using an RF-Wobbler. Symmetry issues?

High Frequency Rotating Ion Beam

A.R. Piriz et al, Plasma Phys. Controlled Fusion 45 (2003) 1733.

- Analysis of symmetry level achieved by a rotating ion beam.
- Analytic model and numerical simulations
- Spatial power profile: rectangular as well as Parabolic
- Temporal power profile: rectangular as well as Parabolic



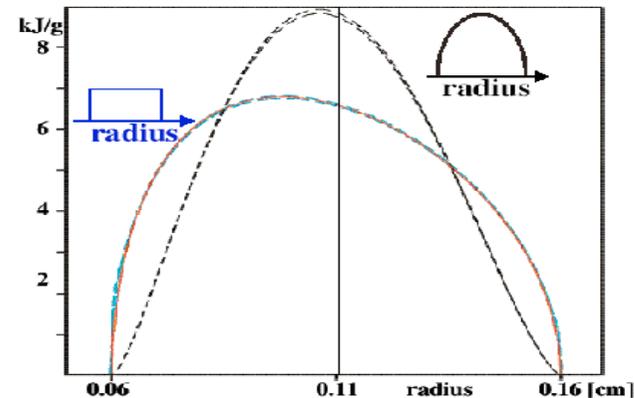
Power Constant in Time

- Circular shape of the focal spot introduces radial distribution in the energy deposition.

- For both cases, the relative pressure asymmetry:

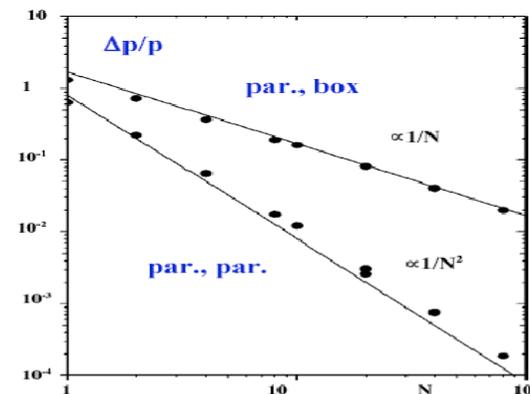
$$\Delta P/P \sim 1/N$$

- $N = \omega \tau$ where $\omega = 2\pi\nu$
- For $\tau = 50$ ns, one would require an $\omega = 2$ GHz to achieve 1 % asymmetry.

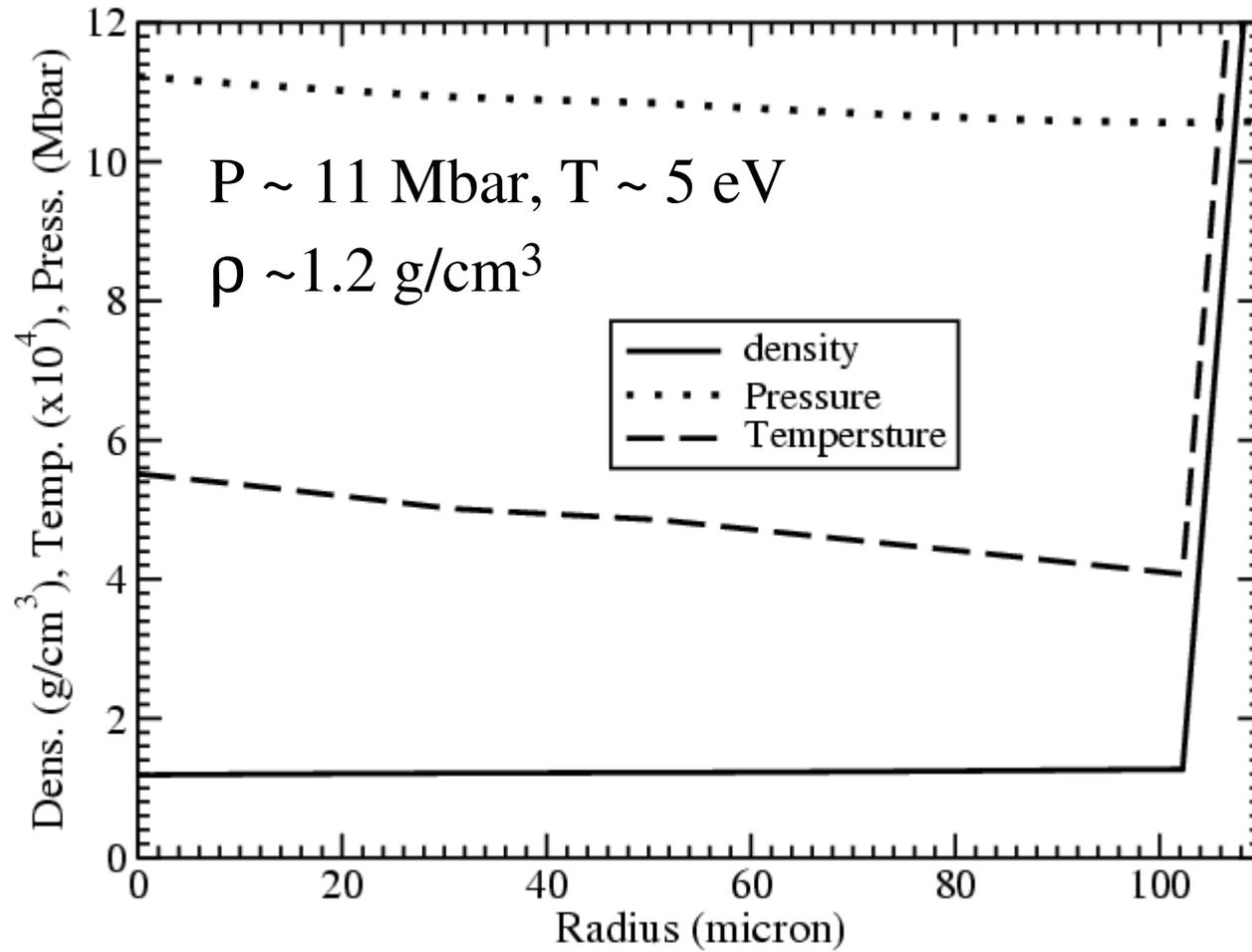


Relative Pressure for Rectangular and Parabolic Temporal Profiles

- With rectangular power temporal profile, one needs $N = 100$ to achieve **1 %** asymmetry. This means for $\tau = 50$ ns, $\omega = 2$ GHz will be required.
- With a parabolic temporal power profile, one would require $N = 10$ so that for $\tau = 50$ ns, $\omega = 0.2$ GHz would be sufficient to achieve **1 %** asymmetry in the driving pressure.



t = 80 ns



Hydrodynamic Stability of the Target

[A.R. Piriz et al, PRE 72 \(2005\) 056313](#)

[N.A. Tahir et al, Phys. High Energy Density 2 \(2006\) 21](#)

1. Rayleigh-Taylor (R-T) instability can occur in the pusher (payload) region. Different situation in two cases.
2. Richtmeyer-Meshkov (R-M) instability can occur if the Au-H interface is corrugated.

[We have investigated these problems in case of LAPLAS targets](#)

Rayleigh-Taylor growth in linear regime

$$\zeta(t) = \zeta_0 \cdot \exp(\gamma t)$$

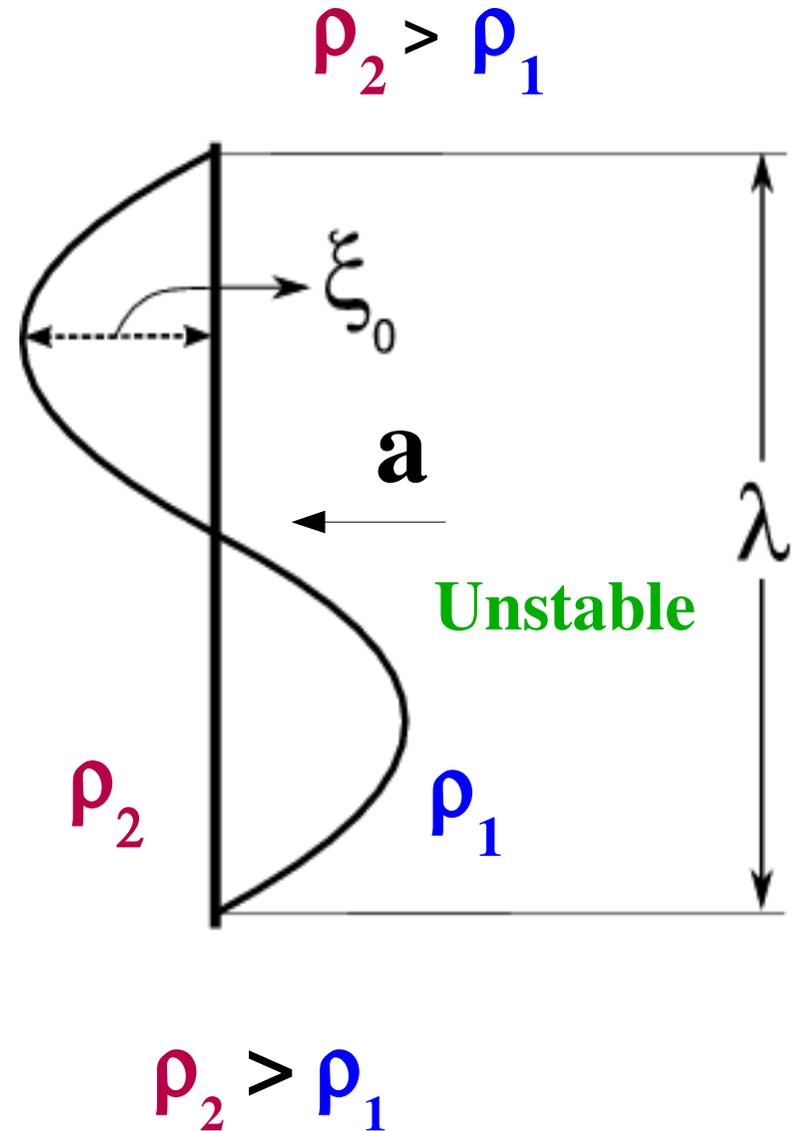
$$\gamma = (\mathbf{a} \cdot \mathbf{k} \cdot \mathbf{A}_T)^{1/2}$$

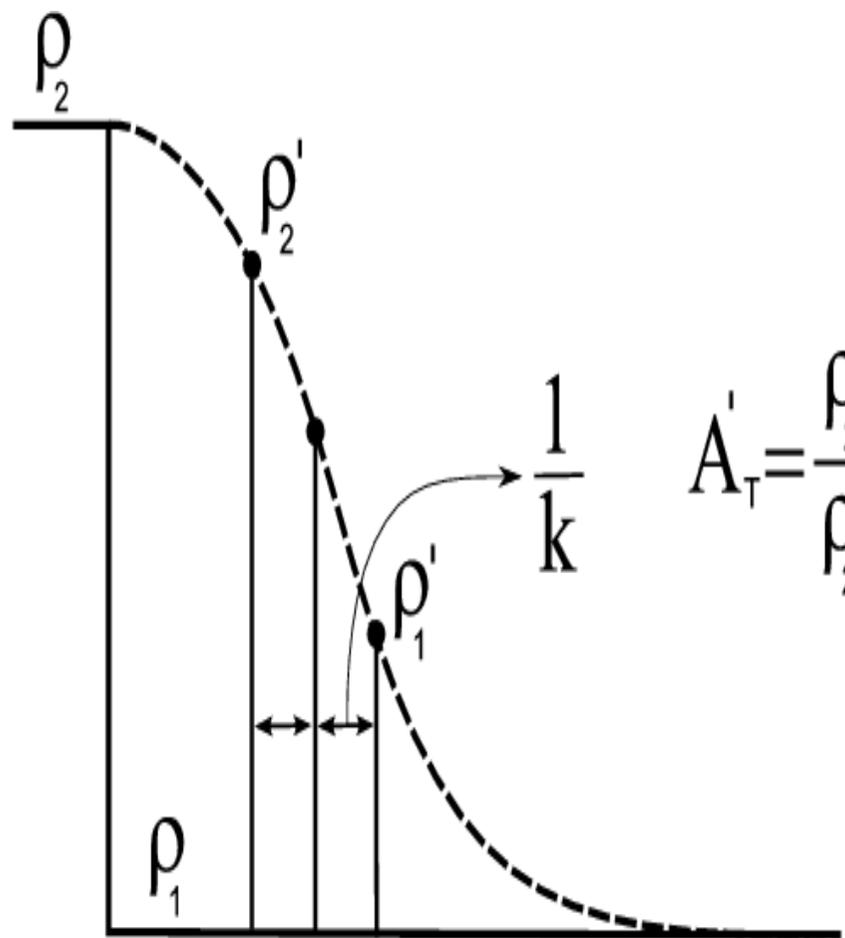
$$\mathbf{A}_T = (\rho_2 - \rho_1) / (\rho_2 + \rho_1)$$

$$\mathbf{k} = 2\pi / \lambda$$

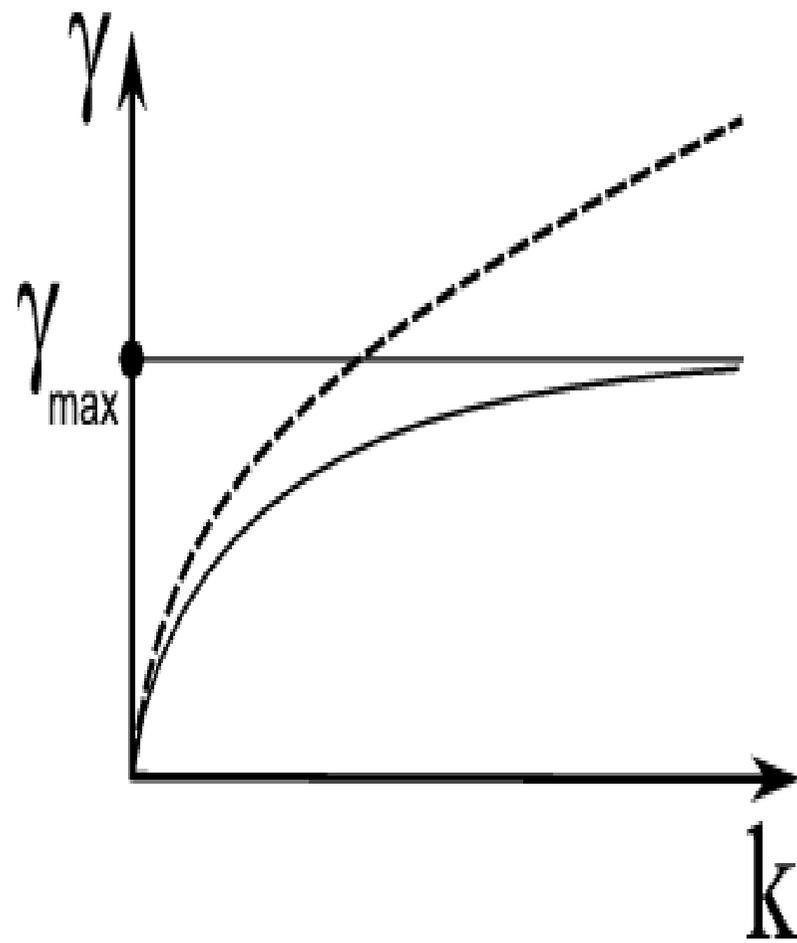
$$\text{If } \rho_2 \gg \rho_1 \text{ then } \mathbf{A}_T \sim 1$$

$$\gamma \sim (\mathbf{k})^{1/2}$$



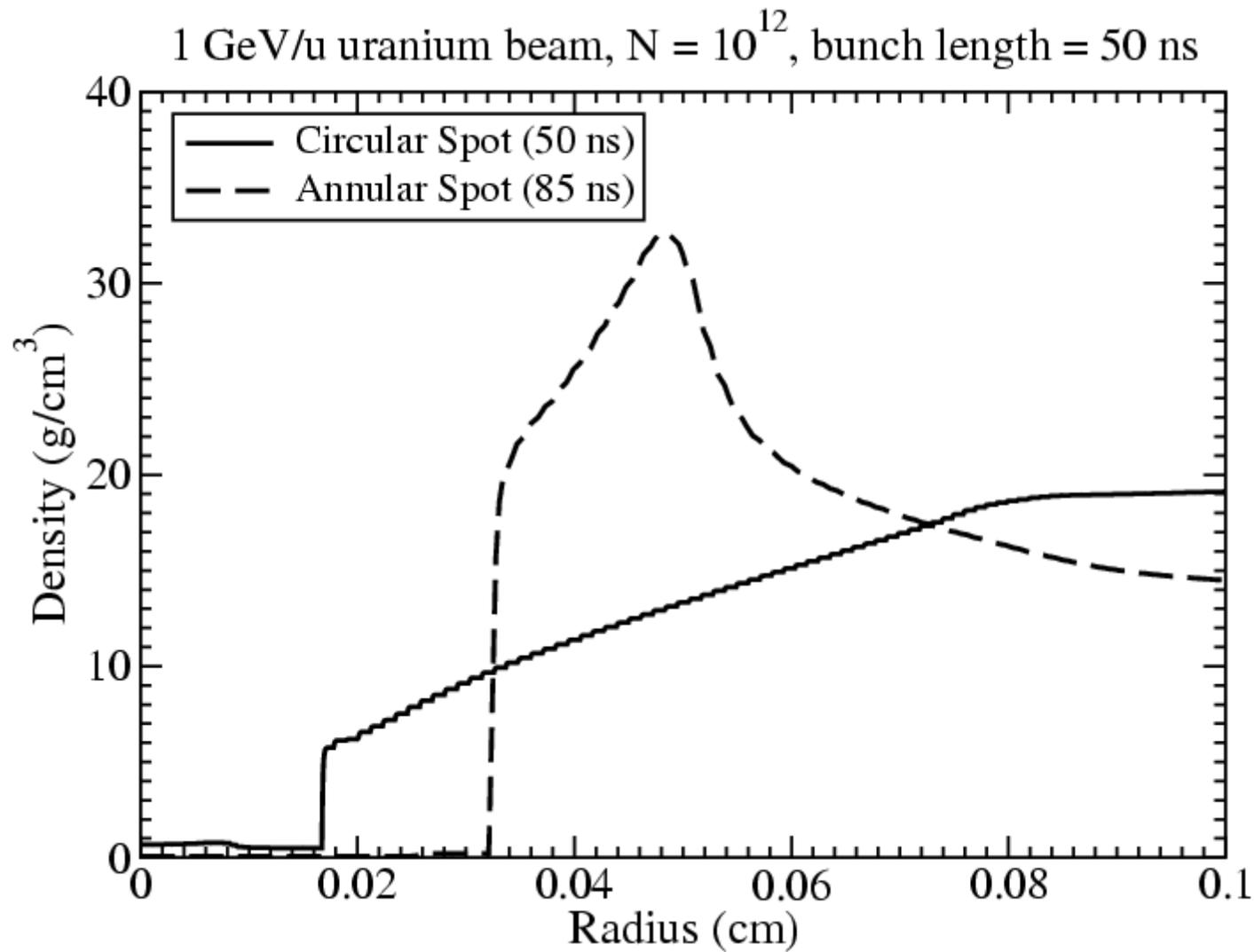


$$A'_T = \frac{\rho_2' - \rho_1'}{\rho_2' + \rho_1'}$$



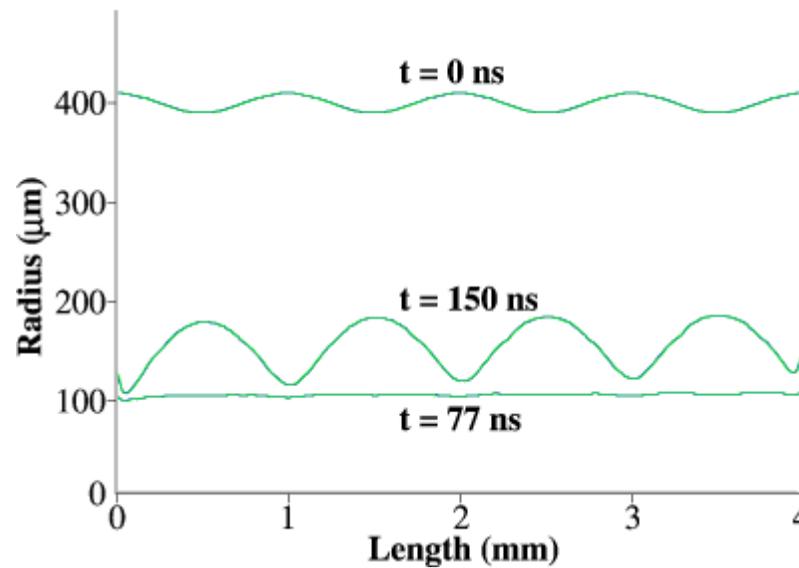
$$\gamma = 2 \times 10^7 \text{ sec}^{-1}$$
$$\Delta t = 5 \times 10^{-8} \text{ sec}$$

e-folding = 1



1. Perturbation along length

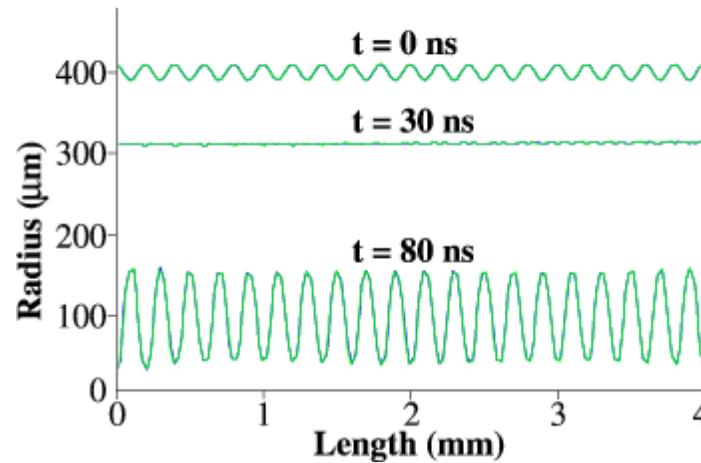
$L = 0.4 \text{ cm}$, $k = 62.8 \text{ cm}^{-1}$, $A = 10 \text{ }\mu\text{m}$, $k \cdot A = 6.28 \times 10^{-2}$



Phase inversion is helpful

With smaller amplitudes the stability situation is very good

$$k = 3.14 \cdot 10^2 \text{ cm}^{-1}, \quad A = 10 \text{ } \mu\text{m}, \quad k \cdot A = 0.314$$



For larger k , phase inversion occurs faster

For smaller amplitudes the stability situation is very good

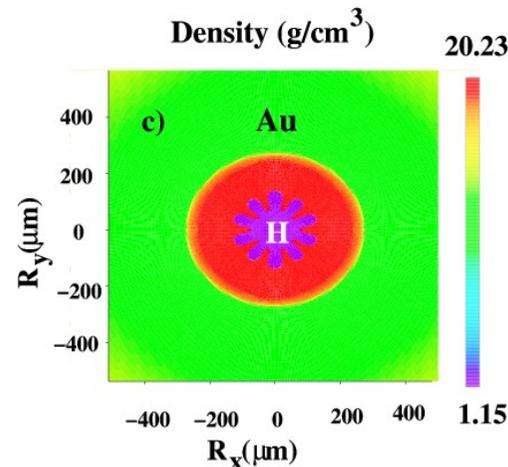
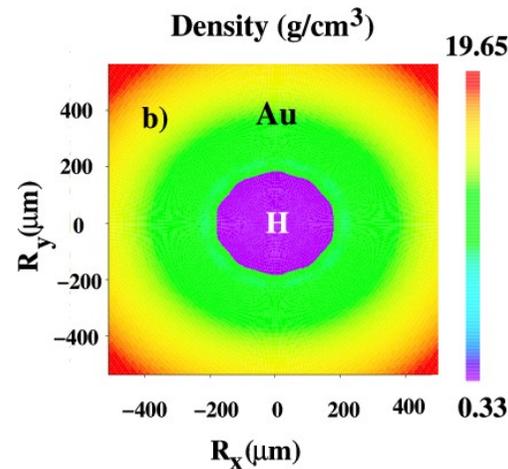
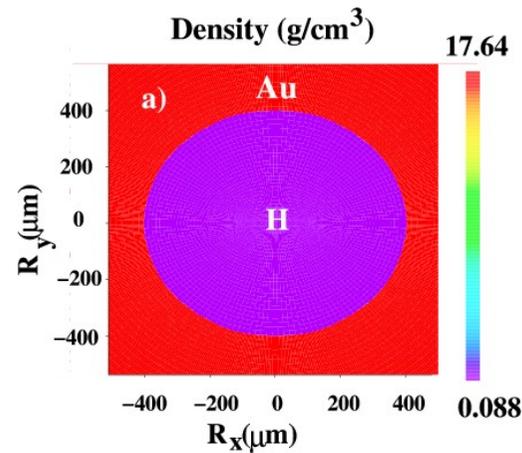
2. Perturbation along circumference

$r = 0.4 \text{ mm}$ and we consider 10 wavelengths.

$$k = 2.5 \cdot 10^2 \text{ cm}^{-1}$$

$$A = 1 \text{ } \mu\text{m}$$

$$k \cdot A = 2.5 \cdot 10^{-2}$$



For:
Smaller wavenumbers
smaller amplitudes
Stability is good

Conceptual Design for Ramp Compression Experiment Using Intense Heavy Ion Beams to Study Material Properties

First Results

FAIR Beam

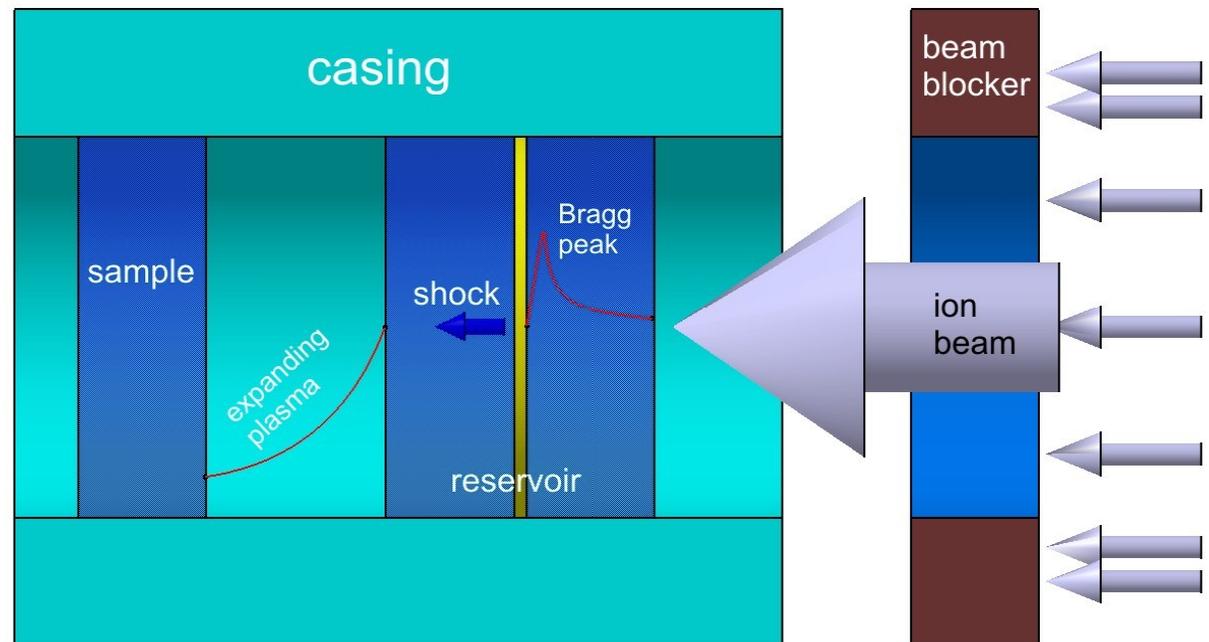
Pb Reservoir

Al Sample

70 % compression

T about 900 K

P of the order of Mbar



III. Study of Safety Aspects with CERN Large Hadron Collider (LHC)

LHC will provide two counter rotating 7 TeV proton beams

2808 proton bunches per beam, **1.15×10^{11}** protons per bunch.

Total number of protons is **3×10^{14}**

Bunch length = **0.5 ns**, Separation between bunches = **25 ns**

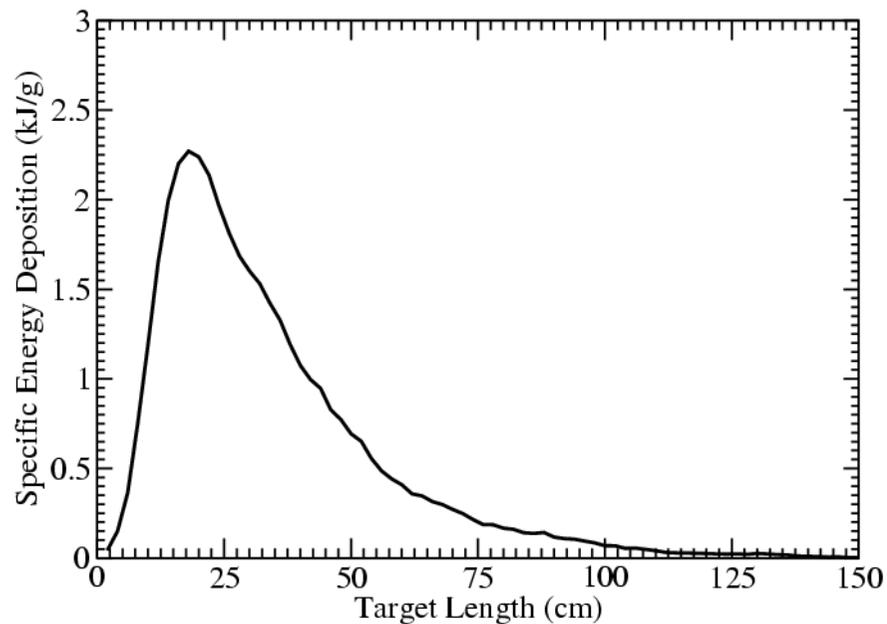
Total length of the bunch train = **89 μ s**

Transverse intensity distribution: Gaussian with **$\sigma = 0.2$ mm**

562 MJ per beam, sufficient to melt **500 kg** of copper

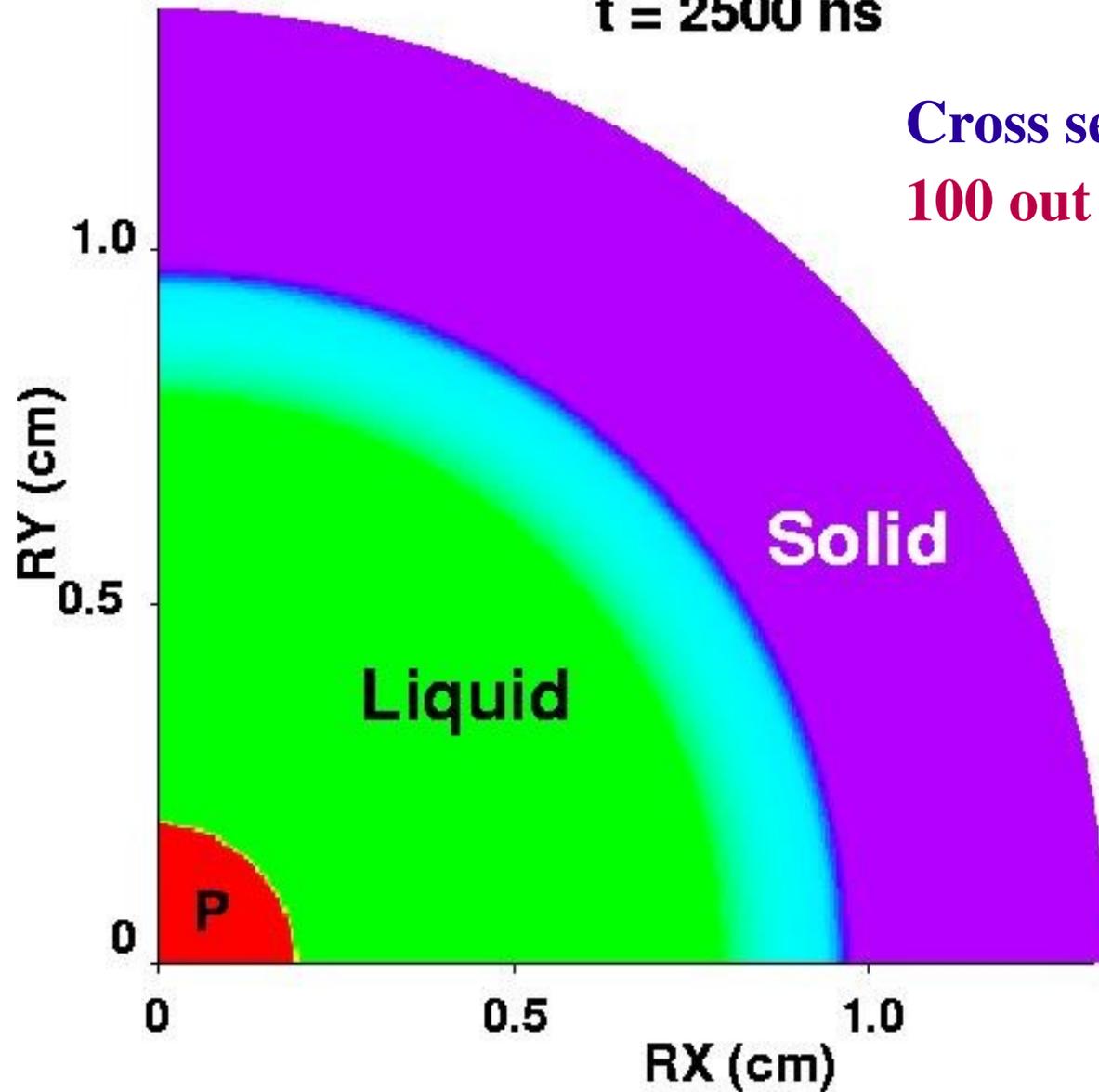
Energy deposition by LHC protons using the FLUKA code

Energy deposited by a single bunch along axis at $r = 0$



- FLUKA is a well established particle interaction and transport Monte Carlo code.
- Capable of simulating all components of the particle cascades in matter up to TeV energies.

Physical State
t = 2500 ns



Cross section of a Cu cylinder
100 out of 2808 bunches delivered
250 kJ/g

N.A. Tahir et al., PRL
94 (2005) 135004.

Physics news Update
April 7, 2005
No: 726#3

APS News, February 7,
2006

CONCLUSIONS:

1. An intense heavy ion beam is a very efficient tool to induce HED states in matter; **large sample size**, **weak gradients**, **long life times**.
2. Construction of the future **FAIR** facility at Darmstadt will enable one to carry out novel and unique experiments in this field.
3. Theoretical studies (simulations + analytic modeling) have shown that an intense heavy ion beam can be employed using three very different schemes to study HED physics.

A). **HIHEX** [**Heavy Ion Heating and Expansion**]

One can use solid as well as porous targets; all interesting physical state, **EHL**, **2PLG**, **CP**, **SCP** can be accessed using the beam at the FAIR facility.

B). **LAPLAS** [**Laboratory PLANetary Sciences**]

The scheme is robust, insensitive to large variations in beam and target parameters, hydrodynamically stable (**Rayleigh-Taylor** and **Richtmeyer-Meshkov**).

C). **Ramp Compression**: Studies of Material properties under dynamic conditions

4. All particle accelerators including the LHC are intrinsically suitable for HED matter studies.

28th International Workshop on HED Physics in Matter

**January 27 – February 1, 2008 at Waldemar-Petersen-Haus
Hirschegg, Austria**

Conference Chairman:

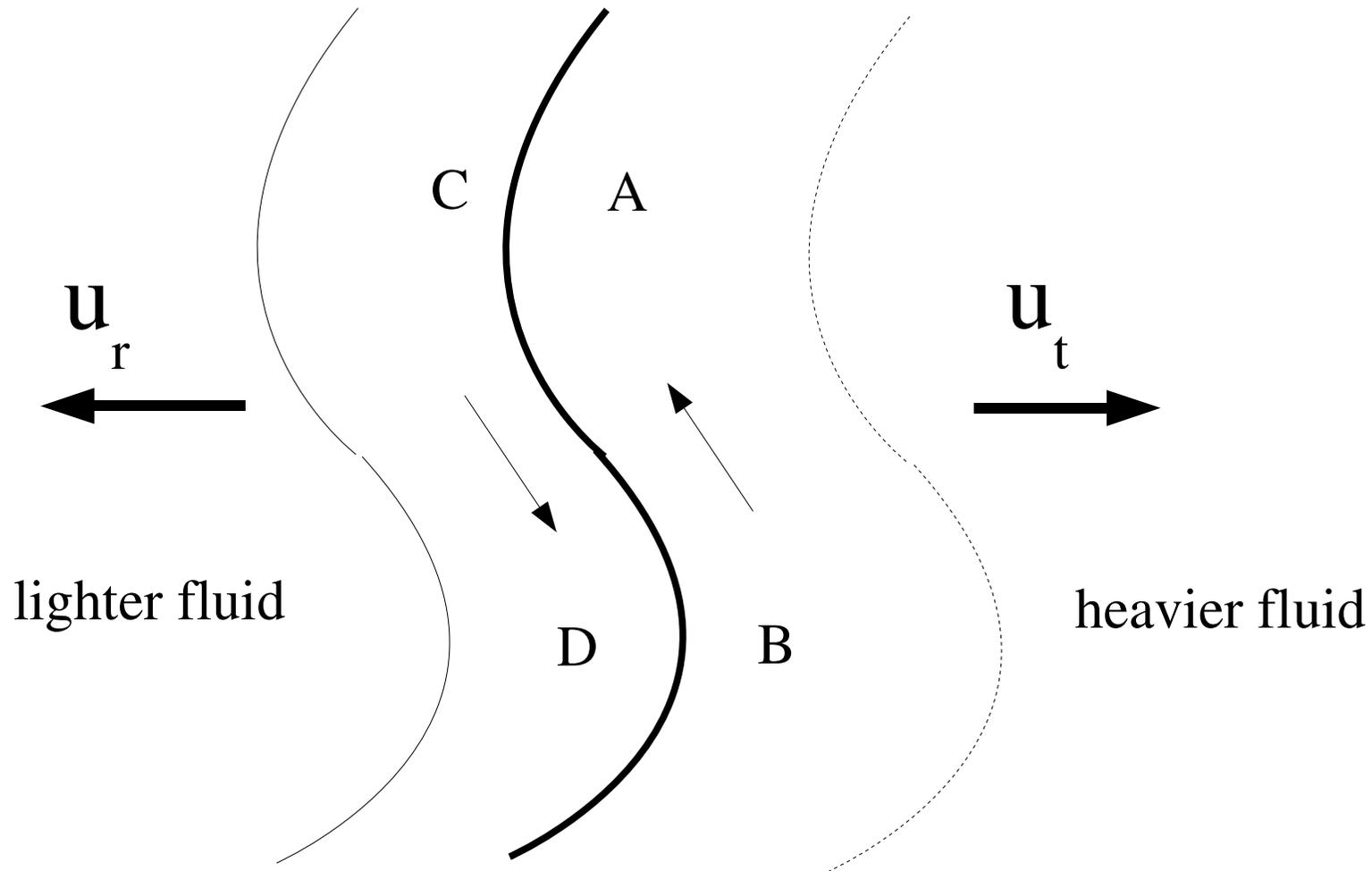
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Schematic Explanation Richt-meyer Meshkov Instability



Gesellschaft fuer Schwerionenforschung (GSI)-Darmstadt Facility for Antiprotons and Ion Research (FAIR)

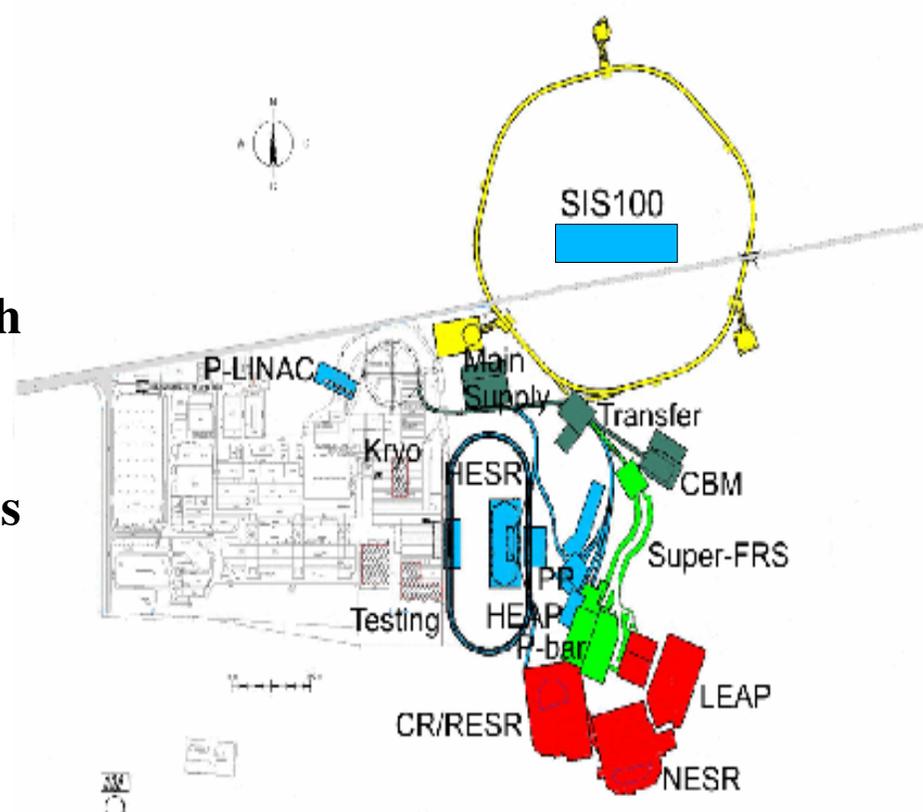
SIS18

10^{11}

U Ions / bunch

197 MeV/u

$\tau = 50 - 100$ ns



SIS100

5×10^{11}

U Ions / bunch

0.4 – 2.7 GeV/u

PP & Super-FRS

4×10^{13}

p / bunch

29 GeV

**Antiproton
Production**

PP target destroyed in one shot

Super-FRS and AP production targets must survive